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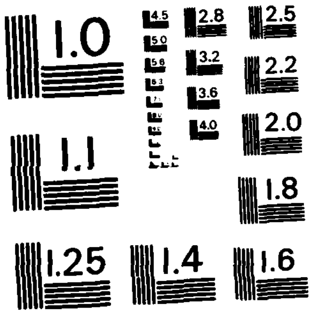


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**REPORT**

**MRL-R-873**

PARA : A COMPUTER SIMULATION CODE FOR PLASMA

DRIVEN ELECTROMAGNETIC LAUNCHERS

Y.-C. Thio*

Approved for Public Release





MARCH, 1983

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A computer code for simulation of rail-type accelerators utilizing a plasma armature has been developed and is described in detail. Some time varying properties of the plasma are taken into account in this code thus allowing the development of a dynamical model of the behaviour of a plasma in a rail-type electromagnetic launcher. The code is being successfully used to predict and analyse experiments on small calibre rail-gun launchers.


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C O N T E N T S

# PARA : A COMPUTER SIMULATION CODE FOR PLASMA DRIVEN ELECTROMAGNETIC LAUNCHERS

## 1. INTRODUCTION

This report presents the mathematical details of PARA, a computer code for simulation of plasma armature rail accelerators. Outlines of the code have been given previously by Thio (1980 [1], 1981 [2], 1982 [3]).

Railgun performance simulation codes have proliferated in the past few years [4-7] owing to the current military and industrial interests in railguns and the role they play in railgun design and system studies. However, to the best knowledge of the author, none of the simulation codes, other than PARA, has the capability of modeling and predicting the detailed physical properties of the plasma armature as well as performance. The earlier codes [5,6] assume a constant value of 200 V as the voltage drop across the plasma armature. More recent codes [7] allow for a time-varying voltage drop by assuming a fixed resistance for the plasma. Other details such as temperature, pressure and length of the plasma are not calculated.

The first serious attempt at studying the behaviour of the plasma armature was made by McNab [8]. Following that, two independent studies were launched almost concurrently: One by Powell and Batteh [9] at the Ballistics Research Laboratory, Aberdeen (1979); the other by Thio [1-3] at the Materials Research Laboratories, Maribyrnong (Australia) where a parallel integrated experimental study of the plasma armature was also undertaken (1980).

The work of McNab was essentially a steady state analysis. Taking McNab's work as a first approximation, Powell and Batteh [9] extended the analysis but still retained the steady-state feature. Specifically, Powell and Batteh assumed constant current and a plasma column in thermodynamic equilibrium. Later, Powell [10] extended the analysis to 2-D. No attempt was made to incorporate the model in a simulation code. Thus no effects associated with the non-linearity of the arc as a circuit component of the driving railgun circuit and no temporal variation of the plasma properties were studied.

PARA represents the first attempt at modeling some of the time-varying properties of the plasma by using a quasi-static approach. More assumptions were made for the plasma model in PARA than by Powell in the interest of mathematical simplification. However, in PARA, the plasma model is embedded in a comprehensive computer code for the simulation of railgun operation. This enables one to follow the dynamical history of the plasma in a typical rail-launcher firing and study the time development of the various plasma parameters including voltage drop, volume, temperature and pressure of the plasma. Knowledge of these plasma properties is particularly important in a systematic treatment of the material problems associated with the eventual realization of plasma-driven electromagnetic launcher technology.

The circuit equations used in PARA are introduced in Section 2 where the major circuit components are identified. In Section 3, the details of the plasma model are presented. For convenience of reference, all pertinent equations used in PARA are assembled in Section 4, and the broad structure of the computer program is outlined in Section 5. The concluding section contains a critique of the present version of PARA and some recommendations for future development of the code.

## 2. CIRCUIT EQUATIONS

### 2.1 The Circuit

The equivalent circuit used for the railgun is shown in Figure 1. The power supply consists of a capacitor bank C, which is connected in series with an inductor $L_o$ via a switch $S_1$ which may be an ignitron or a spark gap. The switch $S_1$ is the main switch which turns on the main discharge. The capacitor bank is also equipped with a crow-bar switch $S_2$, which in the code can be set to turn on at any particular voltage across the capacitor. In practice depending on the actual switch used, there are constraints on the bias voltage which is needed to activate it.

The rails are connected in series with the inductor $L_o$. The reactance in the rails is lumped as a variable inductance $L_r$ and a variable resistance $R_r$. The plasma armature manifests itself as a variable resistor $R_p$ between the rails with $V_{E,5}$ and $V_{E,6}$ the electrode potential drop at each rail. Similarly, for the plasma switches $S_1$ and $S_2$, a resistance ($R_{S,1}$ or $R_{S,2}$) and electrode potential drops ($V_{E,1}$, $V_{E,2}$, $V_{E,3}$ and $V_{E,4}$) are allowed for. In the case of the switches, the resistance is assumed to be constant. Any stray resistance associated with the bus-bars and with any electrical connections in the capacitor crow-bar switch circuit are lumped with the resistances $R_{S,1}$ and $R_{S,2}$. Stray resistance across contact joints in the main railgun circuit are lumped as a fixed resistor $R_{S,3}$. The resistance $R_b$

of the main inductor $L_o$, however, is allowed to vary with time, in an attempt to take account of the skin effect. Any stray inductance in the main driving circuit is also lumped with $L_o$.

In the computation, the coupling between the capacitor-crow-bar circuit and the main driving circuit after the crow-bar $S_2$ is activated is completely ignored. Thus, after $S_2$ is turned on, computation proceeds as if the capacitor bank has been physically removed from the circuit, and the circuit consists of inductances and resistances only.

The electrode drops, $V_{E,1}$, $V_{E,2}$, $V_{E,5}$ and $V_{E,6}$ are lumped as a single voltage $V_{E,B}$, given by

$$V_{E,B} = V_{E,1} + V_{E,2} + V_{E,5} + V_{E,6} \tag{2.1}$$

Similarly, after crow-bar,

$$V_{E,A} = V_{E,3} + V_{E,4} + V_{E,5} + V_{E,6} \tag{2.2}$$

The stray resistances are lumped thus,

$$R_{S,B} = R_{S,1} + R_{S,3} \tag{2.3}$$

before crow-bar, and

$$R_{S,A} = R_{S,2} + R_{S,3} \tag{2.4}$$

after crow-bar. In the current version of PARA, it is assumed that

$$\begin{aligned} V_{E,A} &= V_{E,B} \text{ i.e. } V_{E,1} + V_{E,2} = V_{E,3} + V_{E,4} \\ &\text{and} \\ R_{S,A} &= R_{S,B} \text{ i.e. } R_{S,1} = R_{S,2} \end{aligned} \tag{2.5}$$

## 2.2 The Equations

With switch $S_1$ closed and $S_2$ open, the basic equations governing the temporal behaviour of the circuit are:

$$\frac{dI}{dt} = \frac{V_C - V_E - I(R_S + R_b + R_r + R_p + L'V_{proj})}{L_o + L'z} \qquad (2.6)$$

$$\frac{dV_c}{dt} = -\frac{I}{C} \qquad (2.7)$$

where I is the current in the rails and through the plasma armature and $V_c$ is the voltage across the capacitor; $V_E$ is $V_{E,A}$ or $V_{E,B}$ and $R_s$ is $R_{S,A}$ or $R_{S,B}$; $R_b$, $R_r$ and $R_p$ are variable resistances of the inductor $L_o$, the rails, and the plasma column respectively. L' is the inductance per unit length of the rails, z is the position of the back-end of the projectile and $V_{proj}$ is its velocity.

After the switch $S_2$ closes, the circuit equations (2.6) and (2.7) reduce to a single equation

$$\frac{dI}{dt} = \frac{-V_{E,B} - I(R_{S,B} + R_b + R_r + R_p + L'V_{proj})}{L_o + L'z} \qquad (2.8)$$

For calculating the resistances $R_b$ and $R_r$, the conductors for the inductor, the bus-bars and the rails are assumed to have rectangular cross-sections or cross-sections which can be derived from a small amount of conformal deformation. A skin depth $\delta$ is assumed for these conductors

$$\delta = \left\{\frac{\pi t \eta}{\mu}\right\}^{1/2} \qquad (2.9)$$

which is associated with a step current pulse [11,12], where $\eta$ is the resistivity, $\mu$ permeability and t is time. The usual simple expression for resistance

$$R = \frac{\eta \ell_c}{w_c d} \qquad (2.10)$$

is used for calculating $R_b$ and $R_r$, where $\ell_c$ is the length, $w_c$ the width and d is either the thickness of the conductor or twice the skin depth $2\delta$, whichever is smaller. Velocity-skin effect for the rails is not considered in the present version of PARA.

The yet undefined quantities in the governing equations (2.6) to (2.8) are the position z and the velocity $V_{proj}$ of the projectile, and the resistance $R_p$ of the plasma column, which are treated in the next section.

# 3. PLASMA MODEL

## 3.1 General Assumptions

The following assumptions are made:

(1) The conditions of LTE (Local Thermodynamic Equilibrium), which mean that, (a) the various particle species, electrons, ions and neutral particles all share the same temperature at any particular instant of time; and (b) Saha's equation may be used for calculating the degree of ionization.

(2) The Debye length is sufficiently small for a one-fluid MHD approach to be appropriate.

(3) The electrical conductivity of the plasma is calculated with Spitzer-type expressions. These expressions assume a high degree of ionization and ignore the presence of a magnetic field.

(4) Effects of viscosity are neglected.

(5) For field quantities, only variations in the direction parallel to the rails are considered.

(6) Current density and temperature are assumed uniform throughout the plasma.

(7) The mass of the plasma is assumed to remain constant.

(8) The inertia force in the plasma is assumed to be very much smaller than the Lorentz force and the pressure-gradient force.

(9) The plasma is assumed to be singly ionized from a single atomic species.

## 3.2 Geometry

The geometry is as shown in Figure 2. It is assumed that the plasma is confined to a rectangular region between $z = z_a$ and $z = z_b$, the current flows through the plasma in the negative y-direction with the current density vector $\underline{j} = - j\ \underline{e}_y$, the magnetic induction $\underline{B}$ points in the positive x-direction (into the plane of paper), and the plasma-projectile travels in the positive z-direction with the velocity $\underline{V} = V_{proj}\ \underline{e}_z$. All field quantities are assumed to vary only in the z-direction.

## 3.3 Magnetoplasmadynamic Equations

Following Ferraro and Plumpton [13], the magnetohydrodynamic (MHD) equation for momentum transport is

$$\rho \frac{dV}{dt} + \nabla p = \underline{j} \times \underline{B} + \frac{1}{3} \rho\nu\nabla(\nabla \cdot \underline{v}) + \rho\nu\nabla^2 \underline{v} \qquad (3.1)$$

where $\rho$ is mass density of the plasma, $\underline{v}$ the velocity, $p$ is the pressure which includes both the gas and radiation pressure, $\nu$ is the kinematic coefficient of viscosity.

Viscous effects are ignored ($\nu = 0$) and it is assumed that

$$\rho \frac{dV}{dt} << \nabla p \qquad (3.1a)$$

and so,

$$\rho \frac{dV}{dt} << \underline{j} \times \underline{B} \qquad (3.1b)$$

This is approximately the same as saying that the inertial force acting on the plasma is small compared to the overall Lorentz force which accelerates both the plasma and the projectile. With these assumptions, equation (3.1) reduces to

$$\nabla p = \underline{j} \times \underline{B} = \mu \, \underline{j} \times \underline{H} \qquad (3.2)$$

Use is made of Ampere's law from Maxwell's equations to relate the current density to the magnetic field

$$\nabla \times \underline{H} = \underline{J} \qquad (3.3)$$

In the coordinate system of Figure 2, equations (3.2) and (3.3) have the form

$$\frac{\partial p}{\partial z} = \mu \, jH \qquad (3.4)$$

$$\frac{\partial H}{\partial z} = -j \qquad (3.5)$$

It is then assumed that the current density is uniform in space throughout the plasma so that equations (3.4) and (3.5) can be integrated directly to give the magnetic field within the plasma

$$H(z,t) = H(z_a,t) - j(t)\,(z - z_a) \qquad (3.6)$$

and the pressure distribution in the plasma

$$p(z,t) = p(z_a,t) + \mu \, j(t) \left\{ H(z_a,t)\,(z - z_a) - \frac{j(t)}{2}\,(z - z_a)^2 \right\} \qquad (3.7)$$

The pressure in the plasma is a superposition of two terms: a term $p(z_a,t)$, corresponding to the pressure at the rear boundary $z_a$, and a term (2nd term in (3.7)) associated with the current distributed in the plasma.

The pressure term $p(z_a,t)$ is calculated by considering the mass integral

$$m_p = \int_V \rho \, dV \tag{3.8}$$

The ideal gas equation of state modified by ionization

$$\rho = \frac{p}{RT(1 + \alpha)} \tag{3.9}$$

where $\alpha$ the degree of ionization, is used with expression (3.7), to evaluate the mass integral to give

$$m_p = \frac{V(t)}{RT(t)(1 + \alpha(t))} \left\{p(z_a,t) + \frac{\mu j(t)\ell}{2} [H(z_a,t) - \frac{j\ell}{3}]\right\} \tag{3.10}$$

where $\ell$ is the length of the plasma armature. In the above integration, temperature T has been assumed to be uniform in space. Despite the uniformity of temperature, the degree of ionization is in general not uniform according to Saha's equation if the density and pressure also vary. However, in obtaining the result (3.10), the degree of ionization $\alpha$ is assumed to be uniform in space, again in the interest of mathematical simplicity. Rearranging expression (3.10), the following expression for the pressure at the rear boundary is obtained;

$$p(z_a,t) = \frac{m_p\ RT(t)(1 + \alpha(t))}{V(t)} - \frac{\mu j(t)\ \ell(t)}{2} \{H(z_a,t) - \frac{j(t)\ \ell(t)}{3}\} \tag{3.11}$$

If the plasma is pushing against a closed breech, the pressure at the rear boundary $p(z_a,t)$ is non-zero, giving rise to an additional force on the projectile due to the thermal expansion of the plasma. The term $p(z_a,t)$ is calculated as part of the computation and in this sense the 'explosive' propulsion force due to the expansion of the plasma is accounted for in PARA. The force of explosion associated with the transition between solid and vapour during the fuzing of a metallic foil to generate the plasma is not calculated in PARA. The energy associated with this phase of explosion is however very small and the purturbation caused by it to the overall dynamics of the plasma-projectile should be negligible even in the low energy program RAPID at MRL [2,3].

When the plasma armature is completely confined by magnetic pressure and not in contact with the breech, the pressure $p(z_a,t)$ at the rear boundary is zero. In this case, expression (3.11) yields a relationship between the length of the plasma, the temperature, degree of ionization, the mass of the plasma, and the current in the plasma.

In the computer program, the term $p(z_a,t)$ is automatically constrained to be greater than or equal to zero.

### 3.4 Heat Equation

The simple equation,

$$m_p c \frac{dT}{dt} = I^2 R_p + \int_{\partial V} \underline{F} \cdot \underline{n}\, dS + p \frac{dV}{dt} \tag{3.12}$$

is essentially the equation used to deal with the balance of heat in the current version of PARA, where T is the temperature, c is specific heat of the plasma, $I^2R_p$ is the Joule heating, $\underline{F}$ is the radiative flux, p is the pressure and V is the volume of the plasma. Equation (3.12) may be considered as a statement for the first law of thermodynamics in the present context. The difficulty is to attach a precise meaning to the specific heat c and the pressure p, which in the model is allowed to have spatial variation whereas all other quantities in the equation are uniform in space.

The more general equation for radiative energy transport

$$\frac{d}{dt}\left(u + \frac{1}{2}\rho v^2\right) = \frac{d\varepsilon}{dt} - \operatorname{div} \underline{F} - p \operatorname{div} \underline{v} \tag{3.13}$$

is valid locally throughout the plasma. Here, u is the internal energy density, $\varepsilon$ is density of energy generation by Joule heating, $\underline{F}$ is the radiative flux vector, p is the local pressure and $\underline{v}$ is the local velocity. The variation in the fluid kinetic energy $\frac{1}{2}\rho v^2$ is small compared with the variation in the fluid internal energy (the random kinetic energy of the particles). As a first approximation, (3.13) is rewritten as,

$$\frac{du}{dt} = \frac{d\varepsilon}{dt} - \operatorname{div} \underline{F} - p \operatorname{div} \underline{v} \tag{3.13}$$

Integrating over the volume of the plasma gives,

$$\int_V \frac{du}{dt} dV = \int_V \frac{d\varepsilon}{dt}\, dV - \int_V \operatorname{div} \underline{F}\, dV - \int_V p \operatorname{div} \underline{v}\, dV \tag{3.14}$$

Now,

$$\begin{aligned} \int \frac{d}{dt} &= \int \frac{\partial}{\partial t} + \underline{v} \cdot \nabla \\ &= \frac{d}{dt} \int \end{aligned} \tag{3.15}$$

if $\int \underline{v} \cdot \nabla = \underline{v} \cdot \nabla \int$. The latter is approximately the case if the variation in the velocity field is small, and this is assumed to be the case. It is also assumed that the plasma expands and contracts uniformly, that is div $\underline{v}$ is spatially uniform, so that,

$$\mathrm{div}\ \underline{v} = \dot{V}/V \tag{3.16}$$

where V is the volume of the plasma. With these approximations, (3.14) is reduced to

$$\frac{dU}{dt} = \frac{dQ}{dt} - p_{av}\frac{dV}{dt} \tag{3.17}$$

where U is the total internal energy of the plasma,

$$U = \int_V u\ dV\ .$$

The quantity $p_{av}$ is the volume average of the pressure field,

$$\begin{aligned} p_{av} &= \frac{1}{V}\int_V p\ dV \\ &= p(z_a,t) + \frac{\mu j(t)\ell}{2}\left[H(z_a,t) - \frac{j\ell}{3}\right] \end{aligned} \tag{3.18}$$

upon substituting expression (3.7) for the pressure field within the plasma; or using the equation of state (3.9) and using the same approximation as in evaluating the mass integral, $p_{av}$ can be derived to be,

$$p_{av} = \frac{(1+\alpha)\ m_p\ RT}{V} \tag{3.19}$$

The quantity Q is defined by

$$\begin{aligned} \frac{dQ}{dt} &= \frac{d}{dt}\int_V \varepsilon\ dV - \int_V \nabla \cdot \underline{F}\ dV \\ &= I^2 R_p - \int_{\partial V} \underline{F} \cdot \underline{n}\ ds \end{aligned} \tag{3.20}$$

where the surface integral gives the energy loss by radiative flux through the boundary of the plasma. This is computed assuming the plasma radiates like a black-body:

$$\int_{\partial V} F \cdot n\ dS = 2(wh + h\ell + \ell w)\ \sigma_s T^4$$

where $\sigma_s$ is Stefan's constant for black-body radiation, T is the plasma temperature, h is the height of the bore and w is the width of the bore (separation between the rails).

Equation (3.17) can now be treated unambiguously in terms of the total internal energy of the plasma. For this the following form for the internal energy is assumed;

$$U = \frac{3}{2} m_p RT (1 + \alpha) + \alpha m_p e_I + a VT^4 \qquad (3.21)$$

which is appropriate for a singly ionized, monoatomic species with $e_I$ as the ionization energy per unit mass, and a is the Stefan-Boltzman constant. The corresponding Saha equation for ionization is

$$\frac{\alpha^2}{1 - \alpha} = \left\{\frac{M_r}{N_o}\right\} \left\{\frac{2\pi m_e kT}{h^2}\right\}^{3/2} \left\{\frac{V}{m_p}\right\} \exp \left\{- \frac{q_e V_I}{kT}\right\} \qquad (3.22)$$

where $M_r$ is the atomic weight, $N_o$ Avogadro's number, $m_e$ electron mass, k Boltzman constant, h Planck's constant, $q_e$ electron charge, and $V_I$ the ionization potential.

The total time rate of change of the internal energy may be expressed as

$$\frac{dU}{dt} = \left\{\frac{\partial U}{\partial T}\right\}_V \frac{dT}{dt} + \left\{\frac{\partial U}{\partial V}\right\}_T \frac{dV}{dt}$$

The partial differential coefficients may be calculated from (3.21) and (3.22), and using $E_I/R = q_e V_I/k$, to give

$$\left\{\frac{\partial U}{\partial T}\right\}_V = m_p R(1 + \alpha) \left\{\frac{3}{2} + \frac{\alpha(1 - \alpha)}{(2 - \alpha)(1 + \alpha)} \left\{\frac{3}{2} + \frac{q_e V_I}{kT}\right\}^2 + 12 \frac{p_r}{p_{av}}\right\} \qquad (3.23)$$

$$\left\{\frac{\partial U}{\partial V}\right\}_T = 3 p_r + \frac{\alpha(1 - \alpha)}{(2 - \alpha)(1 + \alpha)} \left\{\frac{3}{2} + \frac{q_e V_I}{kT}\right\} p_{av} \qquad (3.24)$$

where $p_r = \frac{1}{3} aT^4$ is the radiation pressure. It is worth noting that, by definition, the specific heat per unit mass for the plasma at constant volume is

$$c_v = \frac{1}{m_p} \left\{\frac{\partial U}{\partial T}\right\}_V$$

which is expression (3.23) apart from the factor $m_p$. Expression (3.23) is thus an expression for the specific heat $c_v$ for a plasma which takes into account the energy for single ionization and radiation pressure and whose equation of state is that for an ideal gas modified for ionization. In term of $c_v$, the heat development equation is,

$$m_p\, c_v \frac{dT}{dt} = \frac{dQ}{dt} - f_1\, p_{av} \frac{dV}{dt} \tag{3.25}$$

where

$$f_1 = 1 + \frac{\alpha(1-\alpha)}{(2-\alpha)(1+\alpha)} \left\{\frac{3}{2} + \frac{q_e V_I}{kT}\right\} + \frac{3\, p_r}{p_{av}} \tag{3.26}$$

Comparing with (3.12), it can be seen that an unambiguous interpretation of the specific heat c, and the pressure p with the factor $f_1$ as a 'correction' factor has been derived.

### 3.5 Current Density and Boundary Magnetic Field

Before expression (3.7) can be applied to obtain the gas pressure at the base of the projectile, expressions for the current density j(t) and the magnetic field at the rear boundary $H(z_a,t)$ are required. By assumption of a uniform current density within the plasma

$$j(t) = \frac{\gamma_2\, I}{h\ell} \tag{3.27}$$

where I is the total current, $\ell$ the length of the plasma armature, h the height of bore, and $(1 - \gamma_2)$ the fraction of current which is lost through arcing ahead of the projectile; the factor $\gamma_2$ is normally set to 1 in the running of the code.

For calculating the magnetic field $H(z_a,t)$ at the rear boundary, a simple but rigorous approach is to assume the case of infinitely high rails. In that case, it can be shown that the magnetic field in the region between the rails sufficiently far downstream from the plasma is

$$H(z_a,t) = \frac{I}{h} \tag{3.28}$$

This is the approach used by Powell and Batteh [9]. It does, however, tend to overestimate the average field between the rails.

A less rigorous, but perhaps more realistic, approach is to calculate the field in the region between the rails due to thin sheets of current flowing in the inner surface of the rails of finite height and average the field over the bore. This approach is adopted in the current version of PARA, but instead of averaging the field over the bore, it is only averaged along the mid-line between the rails.

The algebraic result is

$$H(z_a,t) = \{\gamma_1(h/2w) + \gamma_2/2\}\ I/h \tag{3.29}$$

where $\gamma_1$ is a function given by

$$\gamma_1(\beta) = \frac{1}{\pi}\left\{\tan^{-1}\beta + \frac{1}{2}\beta\ln(1+\beta^{-2})\right\}$$

### 3.6 Propulsive Force

From (3.7), the pressure at the base of the projectile is given by

$$p(z_b,t) = p(z_a,t) + \mu j(t)\left\{H(z_a,t)\ell - \frac{1}{2}j(t)\ell^2\right\} \tag{3.30}$$

Substituting (3.27) and (3.29) into (3.30)

$$p(z_b,t) = p(z_a,t) + \mu\gamma_2\gamma_1(h/2w)\ (I/h)^2 \tag{3.31}$$

The accelerating force acting on the projectile is then given by

$$\begin{aligned} F_p &= p(z_b,t)\ wh \\ &= p(z_a,t)\ wh + (\mu w/h)\ \gamma_2\gamma_1\ (h/2w)\ I^2 \end{aligned} \tag{3.32}$$

This expression is used in the elementary equation

$$\frac{d^2z}{dt^2} = \frac{F_p}{m} \tag{3.33}$$

to calculate the position z of the projectile.

### 3.7 Plasma Resistance

The resistance of the plasma armature is calculated as:

$$R_p = \frac{\eta_p w}{h\ell} \tag{3.34}$$

where $\eta_p$ is the resistivity of the plasma. Spitzer's expression [14] for a strongly ionized gas in the absence of a magnetic field and ionic charge of unity ($Z = 1$) is used to calculate the resistivity:

$$\eta_p = \frac{65.3 \ln \Lambda}{T^{3/2}} \ \Omega.m \tag{3.35}$$

where

$$\Lambda = 1.238 \times 10^7 \ T^{3/2}/n_e^{1/2}$$

and $n_e$ is the electron density. Though the expression for resistivity is dependent on the electron density which varies as the mass density $\rho$, the dependence is very weak and an average value for the electron number density is used;

$$n_e = \frac{\text{Total number of electrons in the plasma}}{\text{Volume of plasma}}$$

$$= \frac{\alpha N_o m_p}{M_r V} \tag{3.36}$$

where $N_o$ is Avogadro's number, $M_r$ the atomic weight of the atomic species and V the volume of the plasma.

## 4. ASSEMBLY OF EQUATIONS

For convenient reference, this section is a collection of the basic set of equations used by PARA. Equation numbers from the text are shown wherever applicable.

(2.6) $$\frac{dI}{dt} = \frac{V_C - V_E - I(R_s + R_b + R_r + R_p + L'V_{proj})}{L_o + L'z} \tag{4.1}$$

(2.7) $$\frac{dV_c}{dt} = -\frac{I}{C} \tag{4.2}$$

(3.32) $$\frac{dV_{proj}}{dt} = \{p(z_a,t)\ wh + (\mu w/h)\ Y_2 Y_1\ (h/2w)\ I^2\}/(m_p + M) \tag{4.3}$$

$$\frac{dz}{dt} = V_{proj} \tag{4.4}$$

(3.25), (3.20) $$\frac{dT}{dt} = \{I^2R_p - 2(wh + h\ell + \ell w)\ \sigma_s\ T^4 - f_1 p_{av}\ \dot{V}\}/m_p\ c_v \tag{4.5}$$

$$\frac{dQ_p}{dt} = I^2R_p \tag{4.6}$$

$$\frac{dQ_r}{dt} = I^2R_r \tag{4.7}$$

$$\frac{dQ_e}{dt} = I\ V_E \tag{4.8}$$

$$\frac{dQ_{rad}}{dt} = 2\ (wh + H\ell + \ell w)\ \sigma_s\ T^4 \tag{4.9}$$

(2.1), (2.2), (2.5)
$$\begin{aligned} V_E &= V_{E,1} + V_{E,2} + V_{E,5} + V_{E,6} \\ &= V_{E,3} + V_{E,4} + V_{E,5} + V_{E,6} \end{aligned} \tag{4.10}$$

(2.3), (2.4), (2.5) $$R_S = R_{S,1} + R_{S,3} = R_{S,2} + R_{S,3} \tag{4.11}$$

(2.10) $$R_b = \begin{cases} \dfrac{\eta_b\ \ell_b}{w_b\ d_b} & \text{if } d_b < 2\delta_b,\ d_b \text{ inductor thickness} \\[2ex] \dfrac{\eta_b\ \ell_b}{2w_b\ \delta_b} & \text{if } d_b > 2\delta_b,\ \delta_b = \left\{\dfrac{\pi t \eta_b}{\mu}\right\}^{1/2} \end{cases} \tag{4.12}$$

(2.10) $$R_r = \begin{cases} \dfrac{\eta_r\ \ell_r}{w_r\ d_r} & \text{if } d_r < 2\delta_r,\ \text{dr rail thickness} \\[2ex] \dfrac{\eta_r\ \ell_r}{2w_r\ \delta_r} & \text{if } dr > 2\delta_r,\ \delta_r = \left\{\dfrac{\pi t \eta_r}{\mu}\right\}^{1/2} \end{cases} \tag{4.13}$$

| | | | |
|---|---|---|---|
| (3.34), (3.35) | $$R_p = \frac{w}{k\ell}\,\frac{65.3}{T^{3/2}}\,\ell n\,(1.238 \times 10^7\, T^{3/2}/n_e^{1/2})$$ | | (4.14) |
| (3.36) | $$n_e = \frac{\alpha N_o\, m_p}{M_r\, V}$$ | | (4.15) |
| (3.29) | $$L' = (2\mu w/h)\,\gamma_1(h/2w)$$ | | (4.16) |
| (3.29) | $$\gamma_1(\beta) = \frac{1}{\pi}\left\{\tan^{-1}\beta + \frac{1}{2}\beta\,\ln\,(1 + \beta^{-2})\right\}$$ | | (4.17) |
| (3.23) | $$c_v = R(1 + \alpha)\left\{\frac{3}{2} + \frac{\alpha(1 - \alpha)}{(2 - \alpha)(1 + \alpha)}\left(\frac{3}{2} + \frac{q_e\, V_I}{kT}\right)^2 + \frac{4\,aT^4}{p_{av}}\right\}$$ | | (4.18) |
| (3.26) | $$f_1 = 1 + \frac{\alpha(1 - \alpha)}{(2 - \alpha)(1 + \alpha)}\left\{\frac{3}{2} + \frac{q_e\, V_I}{kT}\right\} + \frac{aT^4}{p_{av}}$$ | | (4.19) |
| (3.11) | $$p(z_a,t) = \max\left\{0,\ \frac{m_p RT(t)(1 + \alpha(t))}{V(t)} - \frac{uj(t)\,\ell(t)}{2} \times \left[H(z_a,t) - \frac{j(t)\,\ell(t)}{2}\right]\right\}$$ | | (4.20) |
| (3.29) | $$H(z_a,t) = \{\gamma_1(h/2w) + \gamma_2/2\}\; I/h$$ | | (4.21) |
| (3.22) | $$\alpha^2(1 - \alpha)^{-1} = (M_r/N_o)(2\pi m_e kT/h^2)^{3/2}\,(V/m_p)\,\exp\,[-q_e\, V_I/kT]$$ | | (4.22) |

The physical meanings of the symbols are given below:

| | |
|---|---|
| $I$ | *Current in the railgun circuit* |
| $V_c$ | Voltage across the capacitor bank |
| $V_E$ | Total electrode potential drop in the circuit |
| $R_s$ | Stray resistance, constant in time |
| $R_b$ | Time-dependent resistance of the inductor |
| $R_r$ | Time-dependent resistance of the rails |

| | |
|---|---|
| $R_p$ | Time-dependent resistance of the plasma |
| $L'$ | Inductance per unit length of the rails |
| $L_o$ | Inductance of the storage or pulse-shaping inductor |
| $z$ | Position of projectile |
| $C$ | Capacitance of the capacitor bank |
| $V_{proj}$ | Projectile velocity |
| $P(z_a,t)$ | Pressure at the rear boundary of the plasma |
| $w$ | Rail separation |
| $h$ | Height of that portion of rail exposed to the plasma |
| $\mu$ | Permeability of free space |
| $\gamma_1$ | A geometric function |
| $1-\gamma_2$ | Fraction of current lost through arcing ahead of the projectile. Normally assume $\gamma_2 = 1$. |
| $T$ | Temperature of plasma |
| $\sigma_s$ | Stefan constant for black-body radiation |
| $Q_p$ | Heat dissipated in plasma through ohmic heating |
| $Q_r$ | Heat dissipated in rails through ohmic heating |
| $Q_E$ | Energy dissipated by electrode potential drop |
| $Q_{rad}$ | Energy radiated by plasma |
| $P_{av}$ | Mean pressure within the plasma |
| $c_v$ | Specific heat of the plasma |
| $f_1$ | A thermodynamic function |
| $\eta_b$ | Resistivity of the material of which the inductor is made |
| $\eta_r$ | Rail resistivity |
| $\ell_b$ | Conductor length of inductor |
| $d_b$ | Effective thickness of inductor |
| $w_b$ | Effective width of inductor |

$\ell_r$ Length of rail up to the position of projectile from the breech

$w_r$ Total rail height

$n_e$ Electron number density

$\alpha$ Degree of ionization

$q_e$ Electronic charge

$V_I$ Ionization potential for the atomic species making up the plasma

$k$ Boltzman gas constant

$a$ Stefan-Boltzman constant

$m_p$ Total mass of plasma

$M$ Mass of projectile

$M_r$ Molecular or atomic weight of the ionic species in the plasma

$N_o$ Avogadro's number

$m_e$ Mass of electron

$h$ Planck's constant

$\delta$ Skin depth

Comment: The dimensions $\ell_b$, $d_b$, $w_b$ are specifically designed for the case where the main inductor is a coil made up of flat metallic strips.

## 5. STRUCTURE OF THE PROGRAM

The overlay structure of the program is shown in Figure 3. The names of the subprogram units are displayed within rectangular enclosures. The paths of subprogram calls are indicated by solid lines and the arrows indicate the directions of call. A cross + is a joint in the path whereas a semicircle Ω indicates a bypass. Thus, the main program is named PARA and it calls upon four subroutines: SETUP, NORMAL, EXTRAC and SGUN. Subroutine SETUP handles the input of data and sets up the data array CONDAT. NORMAL normalizes the data in CONDAT to dimensionless quantities. EXTRAC extracts the data required for the first gun segment (PARA can handle guns of more than one segment) and stores them in the array GUNDAT, ready for use by SGUN. SGUN calls upon INTERP to interpret the data in GUNDAT, CAPSEG to simulate a capacitively driven gun segment, and INDSEG to simulate an inductively driven gun segment. CAPSEG calls upon CAPAC for a definition of the system of equations which are essentially equations (4.1)-(4.9) and calls upon RESULT to channel the results of the computation. Similarly INDSEG calls upon INDUCT to obtain the equations appropriate for an inductively driven segment which are essentially the same equations (4.1)-(4.9) with $V_c = 0$ and $dV_c/dt = 0$. It also calls upon RESULTS to output the results of the simulation. CAPSEG also calls upon INDSEG after the capacitor bank is crow-barred. Both INDUCT and CAPAC make use of VETROD, VRAIL and PLASMA to calculate the relevant quantities from the list of definitions (4.10)-(4.22). PLASMA makes use of two further subprogram units PHYCON and MAGCON to treat the case of the plasma being confined by the breech and the case of the plasma being confined completely by the magnetic pressure respectively.

In its prèsent form, computer memory requirement by the program is minimal and is not a consideration in implementing it on most commonly available main frame computers. It may also be implemented on many minicomputers or microcomputers. For some microcomputers, memory requirements may be a consideration. If so, Figure 3 provides a convenient diagram for overlaying the various compiled program modules in linking them together to form a segmented running module.

## 6. CRITIQUE AND RECOMMENDATION FOR FUTURE WORK

As was originally intended, PARA was written and used primarily for planning and designing experiments aimed at elucidating behavior of plasma armatures. It basically forms a first generation code for simulating the structure of the plasma armature. Though the results of its use have exceeded the author's expectations in the extent by which they agree with experimental measurements, qualitatively and quantitatively [15,16], the code as a engineering design tool is still deficient in many ways, both in its model for the driving circuit and for the plasma armature.

For the driving circuit, the action of the main switch and the crow-bar switch are modelled as a fixed resistance together with fixed electrode potential drops. This is unsatisfactory as the user of the code is required to know these values before running the code. Further, the values for these parameters are likely to be dependent on the current and its time history. They certainly depend on the particular type of switch used. The transient behavior of the inductor with respect to its inductance is also not modelled.

For the plasma model, major deficiencies include the assumption of mass constancy, spatial uniformity of current density and temperature, and single-species plasma. None of these assumptions are strictly valid in practice.

In railguns, because of the high temperature and pressure, ablation of materials surrounding the plasma may occur at such a rate that ablation products could have significant effects on the plasma volume, temperature, resistivity and hence its resistance.

The role of boundary-layer effects on the plasma armature in the railgun context are not entirely clear at present. These effects are ignored in the present version of PARA, so also are effects of higher dimensions, 2-D and 3-D.

Another major deficiency of the code lies in its use of the concept of electrode potential drops which are added to the column voltage to provide the total voltage drop across the plasma armature. This is unsatisfactory for two reasons:

(i) Experimentally, only the total voltage drop across the leading edge of the plasma armature can be readily measured,

(ii) Assignment of fixed values for the electrode potential drops in running the code can at best be done at present based upon experience with arcs at much lower currents (below ~ 10 kA) and much lower pressures (below ~ 1 atmosphere). Experience with these relatively low current arcs show that the so-called electrode potential drop varies between 1 V and 20 V depending upon the conditions of the arcs [17]. Despite the long existence of the concept of an electrode potential drop, specific knowledge regarding its magnitude, its variation with current and applied voltage, and its origin remain scarce. Use of the concept in the present version of PARA makes the running of the code somewhat arbitrary and requires some intuition about arcs at this level of current density.

Finally, by the kinetic assumptions of uniform expansion and contraction as well as (3.1a) and (3.1b), effects due to MHD instabilities are ignored.

In view of these deficiencies, the following is recommended:

(i) The assumption of constant plasma mass should be replaced by a model for mass increase to include ablation of rail, sabot and barrel materials due to radiative heating by the arc.

(ii) As railgun plasma armatures are radiation-dominated arcs, more accurate models for radiative heat transfer leading to non-uniform temperature, pressure, density, ionization, and current distribution within the arc should be developed. This may be done in one of two ways: (a) Approximate the process of radiative heat transfer within the plasma as a diffusion process, with the radiative flux $\underline{F}$ being proportional to the gradient of radiation intensity I, that is

$$\underline{F} = \lambda \nabla I$$

This is the approach used by Powell and Batteh [9] and Powell [10] in their 1-D and 2-D static analysis of the arc. (b) Use the exact equation for radiative heat transfer through the use of the radiation integral. The choice between the two methods will depend on the relative computational complexity of the two methods and the accuracy of the first method in the railgun context.

(iii) Models for the plasma sheath between the plasma column and the rails should be developed. Such models should provide information on the so-called electrode potential drop, and define more accurately the transition between the plasma column and the rails. In particular, the transfer of heat between the plasma column and the rails will be more accurately modelled.

(iv) The use of more accurate expressions for plasma resistivity taking into consideration multiple ionization and intense cross magnetic field is warranted.

(v) Since substantial energy loss could be caused by the use of inefficient crow-bar switches in the case of capacitor bank driven railguns, provision should be made in the code for a better model for the operation of the crow-bar switch and the coupling between the crow-bar circuit and the main driving circuit. Models for the crow-bar switch of course depend on the particular method of switching and provision should be made in the form of a user-written subroutine. A better model for the main switch should also be used.

(vi) For very accurate simulation, the transient behavior of the driving inductor with the consequent time-dependent inductance and resistance should be modelled. This again depends on the detailed geometry of the inductor.

(vii) The rail velocity-skin effect should be modelled. A minimum effort here would involve an integral model, at least 2-D, which treats the moving plasma column, plasma sheath and conduction in the rails as a single entity in a consistent way according to the equations of Maxwell and magnetoplasmadynamics.

## 7. ACKNOWLEDGEMENT

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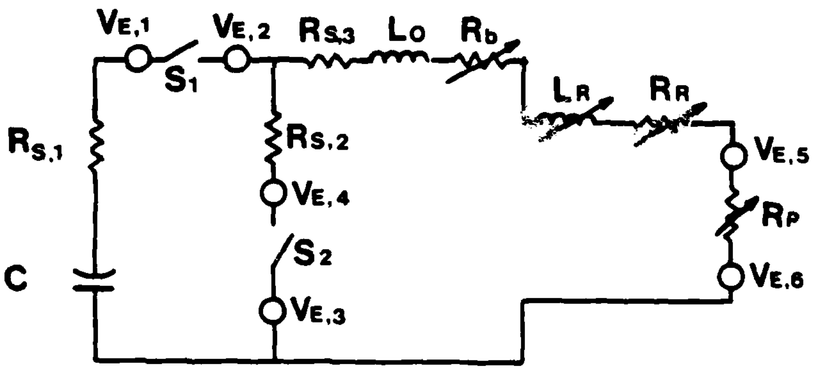


FIGURE 1    Railgun equivalent circuit used in PARA

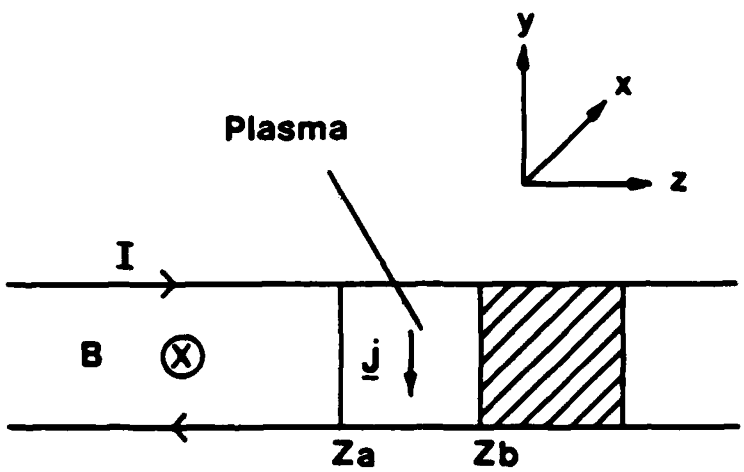


FIGURE 2    Geometry of plasma model

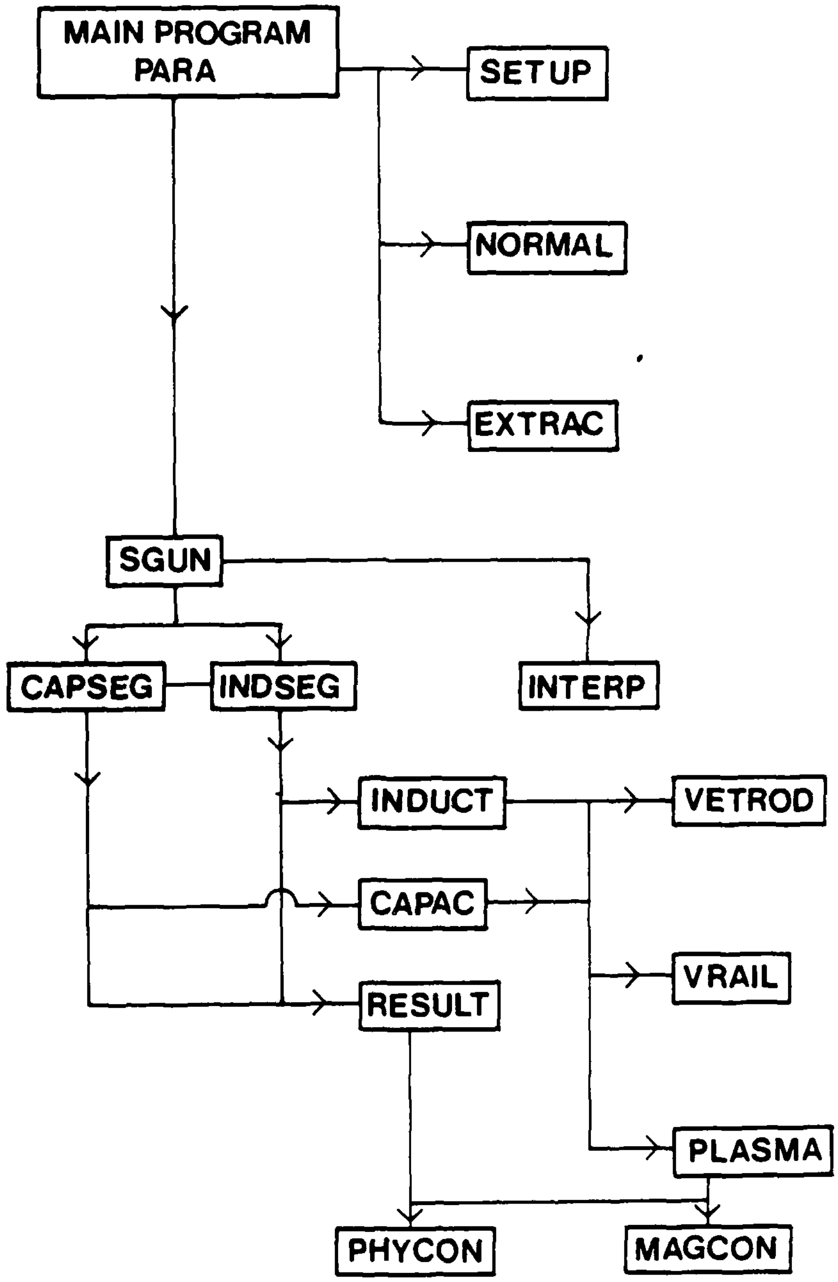


FIGURE 3 Program Overlay Structure

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